E1 transitions between states with n=1 to 6 in helium-like carbon, nitrogen, oxygen, neon, silicon, and argon

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ABSTRACT

Wavelengths and transition rates are given for E1 transitions between singlet ^1S, ^1P, ^1D, and ^1F states, between triplet ^3S, ^3P, and ^3D states, and between triplet $^3P_1$ and singlet $^1S_0$ states in ions of astrophysical interest: helium-like carbon, nitrogen, oxygen, neon, silicon, and argon. All possible E1 transitions between states with $J \leq 3$ and $n \leq 6$ are considered. Energy levels and wave functions used in calculations of the transition rates are obtained from relativistic configuration-interaction calculations that include both Coulomb and Breit interactions.

Subject headings: physical data and processes: atomic data, plasmas

1. Introduction

The emission lines resulting from electron capture by multicharged ions colliding with neutral gases provide a powerful diagnostic probe of astrophysical plasmas. X-rays seen in auroras on Jupiter (Metzger et al. 1983; Waite et al. 1994; Cravens et al. 1995; Kharchenko et al. 1998), in comets (Lisse et al. 1996; Dennerl et al. 1997; Weaver et al. 2001) and the X-ray background (Cravens 2000; Cravens et al. 2001) have been attributed to electron capture by heavy ions.

Several laboratory studies of the X-ray emissions have been carried out (Greenwood et al. 2000; Beiersdorfer et al. 2000; Lubinski et al. 2001; Greenwood et al. 2001; Beiersdorfer et al. 2001; Ma et al. 2001; Flechard et al. 2001; Hasan et al. 2001). The interpretation of the laboratory data and the astrophysical data requires a reliable description of the radiative cascade that follows the capture into excited states.

The cascade lines appearing at extreme ultraviolet wavelengths provide additional probes of the environments in which the multicharged heavy ions are present. For the helium-like ions interesting differences may occur as the nuclear charge of the ions changes. It has long been known that for ions beyond N^{5+} the spin-forbidden $2\,^3P_1 - 1\,^1S_0$ transition is more probable than the allowed $2\,^3P_1 - 2\,^3S_1$ transition (Drake & Dalgarno 1969).

In the most recent National Institute of Standards and Technology (NIST) data compilation (Wiese et al. 1996), recommended transition rates for helium-like C, N, and O are based primarily on nonrelativistic calculations by Cann & Thakkar (1992), who used explicitly correlated wave functions for singlet and triplet S, P, and D states with $n \leq 6$ to calculate energies and dipole oscillator strengths for $S-P$ and $P-D$ transitions in helium-like ions with Z from 2 to 10.

In this paper, we extend the results of previous calculations using relativistic configuration-interaction (CI) wave functions and energies for $(1snl)\,^{2S+1}L_J$ states of helium-like ions with $J \leq 3$, $n \leq 6$, and $Z = 6, 7, 8, 10, 14,$ and 18. We present results here for the allowed singlet-singlet and triplet-triplet transitions. The rates for triplet-triplet transitions are determined by averaging the calculated rates over fine-structure substates. Additionally, we present data for intercombination transitions between $^3P_1$ and $^1S_0$ states.

Relativistic CI calculations of wavelengths and transition probabilities have been carried out previously for E1, M1, and M2 transitions between $n = 1$ and 2 states of helium-like ions (Plante et al. 1995). Nonrelativistic many-body perturbation theory, treating relativistic corrections perturbatively, has also been used to calculate energies of $(1snl)$ states with $n = 2$–5 and $l = 0$–2 (Vainshtein & Safronova 1985). The present calculations extend previous relativistic calculations to $n > 2$ and extend previous nonrelativistic calculations to higher values of Z.

The importance of accurate atomic characteristics for astrophysics was further illustrated by Kharchenko & Dalgarno (2001), where the variability of cometary X-ray emission induced by solar wind ions was studied.

2. Calculation

Relativistic CI calculations were introduced to evaluate precise values of energies of $n = 1$ and 2 states of helium-like ions (Chen et al. 1993; Cheng et al. 1994) and used subsequently to evaluate transition energies and transition rates between states of helium-like ions with $n = 1$ and 2 (Plante et al. 1995). In the present paper, we apply the methods developed in these earlier papers to evaluate wavelengths and rates for E1 transitions between $(1snl)$ states with $n \leq 6$ in various helium-like ions of astrophysical interest. The computational method is summarized in the following paragraphs.

2.1. Wave Functions and Energies

The wave function describing a state with angular momentum J, M in a two-electron ion may be written as

$$\Psi_{JM} = \sum_{i\leq j} c_{ij}\Phi_{ij}(JM), \tag{1}$$

where the quantities c_{ij} are expansion coefficients and where $\Phi_{ij}(JM)$, the configuration state vectors, are given by

$$\Phi_{ij}(JM) = \eta_{ij} \sum_{m_i m_j} \langle j_i m_i, j_j m_j | JM\rangle \; a_i^\dagger a_j^\dagger |0\rangle, \tag{2}$$

in second quantization, with

$$\eta_{ij} = \begin{cases} 1, & i \neq j, \\ 1/\sqrt{2}, & i = j. \end{cases} \tag{3}$$

In the above equations, we use subscripts i to designate quantum numbers (n_i, j_i, l_i, m_i) of one-electron states. The quantities c_{ij}, $\Phi_{ij}(JM)$, and η_{ij} are independent of magnetic quantum numbers m_i and m_j. To construct a state of even or odd parity, one requires the sum of orbital angular momenta $l_i + l_j$ to be either even or odd, respectively. From the symmetry properties of the Clebsch-Gordan coefficients, it can be shown that

$$\Phi_{ij}(JM) = (-1)^{j_i+j_j+J+1}\Phi_{ji}(JM). \tag{4}$$

This relation, in turn, implies that $\Phi_{ii}(JM)$ vanishes unless J is even. The wave-function normalization condition has the form

$$\langle \Psi_{JM}|\Psi_{JM}\rangle = \sum_{i\leq j} c_{ij}^2 = 1. \tag{5}$$

Substituting Ψ_{JM} into the Schrödinger equation $(H_0 + V)\Psi_{JM} = E\Psi_{JM}$, one obtains the following set of linear equations for the expansion coefficients c_{ij}:

$$(\epsilon_i + \epsilon_j)c_{ij} + \sum_{k\leq l} \eta_{ij} V_J(ij;kl)\, \eta_{kl}\, c_{kl} = E c_{ij}\,. \tag{6}$$

The potential matrix in Eq. (6) is

$$\begin{aligned} V_J(ij;kl) = \\ &\sum_L (-1)^{j_j+j_k+L+J} \left\{ \begin{array}{ccc} j_i & j_j & J \\ j_l & j_k & L \end{array} \right\} X_L(ijkl) \\ &+ \sum_L (-1)^{j_j+j_k+L} \left\{ \begin{array}{ccc} j_i & j_j & J \\ j_k & j_l & L \end{array} \right\} X_L(ijlk), \end{aligned} \tag{7}$$

where the quantities $X_L(ijkl)$ are given by

$$X_L(ijkl) = (-1)^L \langle \kappa_i \| C_L \| \kappa_k \rangle \langle \kappa_j \| C_L \| \kappa_l \rangle R_L(ijkl). \tag{8}$$

The coefficients $\langle \kappa_i \| C_L \| \kappa_j \rangle$ in the above equation are reduced matrix elements of normalized spherical harmonics, and the quantities $R_L(ijkl)$ are relativistic Slater integrals (Chen et al. 1993; Plante et al. 1994). In the present calculation, where both the Coulomb and Breit interactions are included in the Hamiltonian,

$$\begin{aligned} X_L(ijkl) \rightarrow\ & X_L(ijkl) \\ & + M_L(ijkl) + N_L(ijkl) + O_L(ijkl)\,, \end{aligned} \tag{9}$$

where $M_L(ijkl)$, $N_L(ijkl)$, and $O_L(ijkl)$ are magnetic Slater integrals (Johnson et al. 1988).

Identification of the levels obtained by solving the CI equations was aided by comparison with the online NIST database (2001).

2.2. Transition Amplitudes and Rates

Using the CI wave functions discussed in Sec. 2.1 for both the initial and final states and carrying out the sums over magnetic substates, one obtains the following expression for the reduced electric-dipole matrix element

$$\begin{aligned} \langle F||D||I\rangle = -\sqrt{[J_I][J_F]} \sum_{\substack{m\le n \\ r\le s}} \eta_{rs}\, \eta_{mn}\, c^{(F)}_{rs}\, c^{(I)}_{mn} \times \\ \Bigg\{ (-1)^{j_r+j_s+J_I} \begin{Bmatrix} 1 & J_I & J_F \\ j_s & j_r & j_m \end{Bmatrix} \langle r||d||m\rangle \delta_{ns} \\ + (-1)^{j_r+j_n} \begin{Bmatrix} 1 & J_I & J_F \\ j_s & j_r & j_n \end{Bmatrix} \langle r||d||n\rangle \delta_{ms} \\ + (-1)^{J_F+J_I+1} \begin{Bmatrix} 1 & J_I & J_F \\ j_r & j_s & j_m \end{Bmatrix} \langle s||d||m\rangle \delta_{nr} \\ + (-1)^{j_r+j_n+J_F} \begin{Bmatrix} 1 & J_I & J_F \\ j_r & j_s & j_n \end{Bmatrix} \langle s||d||n\rangle \delta_{mr} \Bigg\}, \end{aligned} \tag{10}$$

where $[J] = 2J+1$. The one-electron reduced matrix elements $\langle m\|d\|n\rangle$ in Eq. (10) are given by

$$\begin{aligned} \langle \kappa_i||d||\kappa_j\rangle = \frac{3}{k}\langle \kappa_i||C_1||\kappa_j\rangle \\ \int_0^\infty dr \Bigg\{ j_1(kr)[P_i(r)P_j(r) + Q_i(r)Q_j(r)] \\ + j_2(kr)\Bigg[\frac{\kappa_i-\kappa_j}{2}[P_i(r)Q_j(r) + Q_i(r)P_j(r)] \\ + [P_i(r)Q_j(r) - Q_i(r)P_j(r)]\ \Bigg] \Bigg\}, \end{aligned} \tag{11}$$

in length form, and

$$\begin{aligned} \langle \kappa_i||d||\kappa_j\rangle = \frac{3}{k}\langle \kappa_i||C_1||\kappa_j\rangle \\ \int_0^\infty dr \Bigg\{ -\frac{\kappa_i-\kappa_j}{2}\left[\frac{dj_1(kr)}{d\,kr} + \frac{j_1(kr)}{kr}\right] \times \\ [P_i(r)Q_j(r) + Q_i(r)P_j(r)] \\ + \frac{j_1(kr)}{kr}\,[P_i(r)Q_j(r) - Q_i(r)P_j(r)] \Bigg\}, \end{aligned} \tag{12}$$

in velocity form. In Eqs. (11) and (12), the quantities $P_i(r)$ and $Q_i(r)$ are large- and small-component radial Dirac wave functions for state i and $j_l(kr)$ is a spherical Bessel function of order l; $k = 2\pi/\lambda$ being the magnitude of the wave vector. These dipole matrix elements are fully retarded. The dipole transition rates are given in terms of the dipole matrix elements by

$$A_{FI} = \frac{2.0613\times 10^{18}}{[J_F]\lambda^3} S_{FI}, \tag{13}$$

where $S_{FI} = |\langle F||D||I\rangle|^2$ is the line-strength of the transition (atomic units) and λ is the transition wavelength (Å).

3. Discussion of Tables

We solve the CI-equation (6) using the method described in Chen et al. (1993) to obtain wave functions for $(1snl)\ ^{2S+1}L_J$ states with $J \le 3$, $S = 0$ & 1, and $n \le 6$ for helium-like ions with $Z = 6$, 7, 8, 10, 14, and 18. The energies obtained from the CI calculations are in precise agreement with earlier relativistic calculations (Plante et al. 1994) and in agreement to parts in 10^4 with the

nonrelativistic CI calculations of Cann & Thakkar (1992). The wavelengths for transitions between nearly degenerate levels are less accurate than the level energies owing to cancellation. The present wavelengths agree with NIST tabulations of measured wavelengths (Wiese et al. 1996) to better than 0.02% for $\lambda < 200$ Å, to better than 0.2% for $200 \leq \lambda < 2000$ Å, and to better than 2% for $\lambda < 20000$ Å. Oscillator strengths from the present calculation agree precisely with those given in Plante et al. (1995) for transitions between states with with $n = 1$ and 2; they are also in close agreement (typically 0.01%) with values from Cann & Thakkar (1992). Transition rates agree with the tabulated NIST values (Wiese et al. 1996) to better than 0.5% for $\lambda < 200$ Å, to better than 1% for $200 \leq \lambda < 2000$ Å, and to better than 2% for $\lambda < 20000$Å.

Results of our calculations are given in Tables 1–12. Although we quote five significant figures for wavelengths and four significant figures for transition rates in these tables, the reader is cautioned that the accuracy of the wavelengths (and consequently the transition rates) as determined by the comparisons discussed above is substantially smaller for larger wavelengths. Length-form and velocity-form matrix elements for these transitions are in close agreement; however, there are small residual differences between length-form and velocity-form matrix elements caused by our neglect of contributions from negative-energy states. As discussed in Plante et al. (1995), these differences, when evaluated perturbatively, contribute only to velocity-form matrix elements, and bring velocity-form matrix elements into precise agreement with the corresponding length-form matrix elements. In the present tabulation, we list transition rates obtained from length-form calculations only.

In Tables 1–6, we present wavelengths and transition rates for singlet-singlet transitions of the type $(1snl)\,^1L - (1sml')\,^1L'$ with L and L' ranging through S, P, D, F. With the exception of the $n\,^1P - m\,^1S$ transitions listed in Table 1, $n - n$ transitions (which have wavelengths $\sim 10^5$ to 10^6 Å and transition rates $< 10^5$ s^{-1}) are omitted from the tables since *ab-initio* calculations for such cases are unreliable.

In Tables 7–10 we present wavelengths and transition rates for triplet-triplet transitions of the type $(1snl)\,^3L - (1sml')\,^3L'$ with L and L' ranging over S, P, D. In the astrophysical applications mentioned in the introduction, the fine-structure of the transitions is unresolved. We therefore average the triplet-triplet rates over individual fine-structure substates J_I, J_F. The average rates $\bar{A}$ listed in the tables are given by

$$\bar{A} = \frac{\sum_{J_I,J_F}[J_F]A_{FI}}{3[L_F]}. \tag{14}$$

(Note that $3[L_F] = \sum_{J_F}[J_F]$ for triplet states.) Multiplet-average wavelengths $\bar{\lambda}$ are also listed in the tables. For reasons given in the previous paragraph, we include $n - n$ transition data only for the $n\ ^3P - m\ ^3S$ transitions (Table 7).

The intercombination transitions between $n\,^3P_1$ states and $m\ ^1S_0$ states, which are comparable in size to allowed transitions for highly-charged ions, are listed in Tables 11 & 12.

In summary, we present accurate wavelengths and transition rates for allowed singlet-singlet and triplet-triplet transitions and for intercombination transitions between triplet $^3P_1$ and singlet $^1S_0$ states with $n \leq 6$ in helium-like, carbon, nitrogen, oxygen, neon, silicon, and argon for use in the analysis of astrophysical plasmas.

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Table 1

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$1\,^1S_0$		$2\,^1S_0$		$3\,^1S_0$		$4\,^1S_0$		$5\,^1S_0$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
					He-like carbon					
$2\,^1P_1$	40.266	8.862[11]	3524.7	1.672[07]						
$3\,^1P_1$	34.972	2.551[11]	247.31	1.277[10]	12160.	2.440[06]				
$4\,^1P_1$	33.426	1.064[11]	186.35	5.764[09]	711.69	1.663[09]	29083.	5.936[05]		
$5\,^1P_1$	32.754	5.420[10]	167.22	3.000[09]	495.34	9.318[08]	1543.0	3.897[08]	57105.	1.959[05]
$6\,^1P_1$	32.399	3.186[10]	158.36	1.780[09]	424.88	5.638[08]	1017.4	2.514[08]	2838.4	1.288[08]
					He-like nitrogen					
$2\,^1P_1$	28.786	1.806[12]	2893.3	2.098[07]						
$3\,^1P_1$	24.900	5.149[11]	173.39	2.690[10]	9972.0	3.072[06]				
$4\,^1P_1$	23.771	2.141[11]	130.30	1.205[10]	498.19	3.531[09]	23835.	7.489[05]		
$5\,^1P_1$	23.281	1.089[11]	116.84	6.259[09]	345.82	1.965[09]	1079.5	8.316[08]	46755.	2.478[05]
$6\,^1P_1$	23.024	6.328[10]	110.62	3.667[09]	296.47	1.172[09]	710.40	5.268[08]	1989.4	2.721[08]
					He-like oxygen					
$2\,^1P_1$	21.600	3.302[12]	2446.6	2.547[07]						
$3\,^1P_1$	18.627	9.344[11]	128.24	5.039[10]	8427.3	3.738[06]				
$4\,^1P_1$	17.767	3.876[11]	96.194	2.246[10]	368.10	6.654[09]	20139.	9.120[05]		
$5\,^1P_1$	17.395	1.970[11]	86.204	1.164[10]	255.01	3.683[09]	797.24	1.571[09]	39507.	3.018[05]
$6\,^1P_1$	17.199	1.146[11]	81.591	6.828[09]	218.48	2.198[09]	523.52	9.925[08]	1468.2	5.165[08]
					He-like neon					
$2\,^1P_1$	13.446	8.853[12]	1852.6	3.542[07]						
$3\,^1P_1$	11.546	2.478[12]	78.251	1.397[11]	6375.9	5.214[06]				
$4\,^1P_1$	10.999	1.024[12]	58.547	6.182[10]	224.32	1.859[10]	15231.	1.274[06]		
$5\,^1P_1$	10.764	5.196[11]	52.427	3.194[10]	155.00	1.021[10]	485.61	4.405[09]	29849.	4.228[05]
$6\,^1P_1$	10.639	3.008[11]	49.607	1.864[10]	132.70	6.051[09]	318.10	2.752[09]	894.55	1.446[09]
					He-like silicon					
$2\,^1P_1$	6.6466	3.757[13]	1195.5	6.276[07]						
$3\,^1P_1$	5.6796	1.037[13]	37.807	6.156[11]	4105.5	9.302[06]				
$4\,^1P_1$	5.4036	4.270[12]	28.214	2.703[11]	108.26	8.246[10]	9801.1	2.278[06]		
$5\,^1P_1$	5.2846	2.161[12]	25.246	1.392[11]	74.607	4.495[10]	234.26	1.961[10]	19189.	7.586[05]
$6\,^1P_1$	5.2221	1.244[12]	23.880	8.076[10]	63.822	2.644[10]	153.05	1.211[10]	431.60	6.426[09]
					He-like argon					
$2\,^1P_1$	3.9478	1.071[14]	816.70	1.133[08]						
$3\,^1P_1$	3.3647	2.931[13]	22.162	1.790[12]	2793.9	1.697[07]				
$4\,^1P_1$	3.1989	1.203[13]	16.521	7.826[11]	63.436	2.402[11]	6661.5	4.173[06]		
$5\,^1P_1$	3.1275	6.078[12]	14.779	4.024[11]	43.669	1.305[11]	137.25	5.717[10]	13045.	1.389[06]
$6\,^1P_1$	3.0900	3.535[12]	13.976	2.358[11]	37.335	7.749[10]	89.522	3.557[10]	252.45	1.896[10]

Table 2

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$2\,^1P_1$		$3\,^1P_1$		$4\,^1P_1$		$5\,^1P_1$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
				He-like carbon				
$3\,^1S_0$	271.92	5.707[09]						
$4\,^1S_0$	198.09	2.292[09]	776.10	1.565[09]				
$5\,^1S_0$	176.09	1.141[09]	521.09	7.539[08]	1677.3	5.361[08]		
$6\,^1S_0$	166.09	6.613[08]	442.23	4.272[08]	1065.6	2.954[08]	3079.7	2.234[08]
				He-like nitrogen				
$3\,^1S_0$	187.92	1.127[10]						
$4\,^1S_0$	137.23	4.542[09]	536.18	3.110[09]				
$5\,^1S_0$	122.07	2.265[09]	361.01	1.505[09]	1158.7	1.070[09]		
$6\,^1S_0$	115.18	1.301[09]	306.71	8.458[08]	738.89	5.865[08]	2132.4	4.418[08]
				He-like oxygen				
$3\,^1S_0$	137.55	2.013[10]						
$4\,^1S_0$	100.63	8.131[09]	392.41	5.583[09]				
$5\,^1S_0$	89.555	4.057[09]	264.73	2.708[09]	847.91	1.925[09]		
$6\,^1S_0$	84.510	2.336[09]	225.03	1.527[09]	541.73	1.060[09]	1559.5	7.983[08]
				He-like neon				
$3\,^1S_0$	82.762	5.227[10]						
$4\,^1S_0$	60.698	2.117[10]	236.11	1.460[10]				
$5\,^1S_0$	54.052	1.057[10]	159.72	7.105[09]	510.17	5.052[09]		
$6\,^1S_0$	51.022	6.066[09]	135.88	3.995[09]	326.94	2.783[09]	938.91	2.094[09]
				He-like silicon				
$3\,^1S_0$	39.416	2.149[11]						
$4\,^1S_0$	28.981	8.726[10]	112.47	6.054[10]				
$5\,^1S_0$	25.825	4.356[10]	76.290	2.954[10]	243.03	2.100[10]		
$6\,^1S_0$	24.385	2.490[10]	64.957	1.655[10]	156.22	1.157[10]	447.49	8.696[09]
				He-like argon				
$3\,^1S_0$	22.967	6.071[11]						
$4\,^1S_0$	16.905	2.467[11]	65.549	1.715[11]				
$5\,^1S_0$	15.069	1.232[11]	44.514	8.380[10]	141.66	5.956[10]		
$6\,^1S_0$	14.229	7.123[10]	37.903	4.753[10]	91.101	3.323[10]	260.35	2.495[10]

Table 3

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$2\,^1P_1$		$3\,^1P_1$		$4\,^1P_1$		$5\,^1P_1$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
				He-like carbon				
$3\,^1D_2$	267.28	3.930[10]						
$4\,^1D_2$	197.03	1.229[10]	760.16	4.410[09]				
$5\,^1D_2$	175.67	5.567[09]	517.36	2.096[09]	1639.3	9.415[08]		
$6\,^1D_2$	165.88	3.062[09]	440.75	1.169[09]	1057.1	5.468[08]	3009.5	2.905[08]
				He-like nitrogen				
$3\,^1D_2$	185.22	8.137[10]						
$4\,^1D_2$	136.62	2.555[10]	526.87	9.117[09]				
$5\,^1D_2$	121.82	1.159[10]	358.81	4.344[09]	1136.4	1.944[09]		
$6\,^1D_2$	115.05	6.319[09]	305.80	2.401[09]	733.62	1.121[09]	2089.1	5.934[08]
				He-like oxygen				
$3\,^1D_2$	135.83	1.501[11]						
$4\,^1D_2$	100.23	4.734[10]	386.47	1.682[10]				
$5\,^1D_2$	89.394	2.151[10]	263.33	8.033[09]	833.67	3.585[09]		
$6\,^1D_2$	84.429	1.176[10]	224.45	4.454[09]	538.42	2.075[09]	1532.3	1.096[09]
				He-like neon				
$3\,^1D_2$	81.925	4.025[11]						
$4\,^1D_2$	60.504	1.284[11]	233.20	4.529[10]				
$5\,^1D_2$	53.972	5.853[10]	159.02	2.173[10]	503.17	9.658[09]		
$6\,^1D_2$	50.981	3.199[10]	135.59	1.205[10]	325.26	5.593[09]	925.25	2.945[09]
				He-like silicon				
$3\,^1D_2$	39.098	1.628[12]						
$4\,^1D_2$	28.907	5.316[11]	111.37	1.860[11]				
$5\,^1D_2$	25.795	2.445[11]	76.026	9.014[10]	240.37	3.985[10]		
$6\,^1D_2$	24.369	1.339[11]	64.845	5.010[10]	155.57	2.318[10]	442.21	1.215[10]
				He-like argon				
$3\,^1D_2$	22.791	4.502[12]						
$4\,^1D_2$	16.864	1.475[12]	64.938	5.142[11]				
$5\,^1D_2$	15.052	6.801[11]	44.368	2.501[11]	140.19	1.102[11]		
$6\,^1D_2$	14.220	3.761[11]	37.846	1.403[11]	90.770	6.481[10]	257.67	3.390[10]

Table 4

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$3\,^1D_2$		$4\,^1D_2$		$5\,^1D_2$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
			He-like carbon			
$4\,^1P_1$	745.56	1.953[08]				
$5\,^1P_1$	511.51	8.443[07]	1610.1	1.077[08]		
$6\,^1P_1$	436.72	4.505[07]	1046.2	5.503[07]	2954.2	5.631[07]
			He-like nitrogen			
$4\,^1P_1$	518.22	4.100[08]				
$5\,^1P_1$	355.35	1.773[08]	1119.3	2.263[08]		
$6\,^1P_1$	303.45	9.376[07]	727.44	1.145[08]	2058.9	1.170[08]
			He-like oxygen			
$4\,^1P_1$	381.00	7.648[08]				
$5\,^1P_1$	261.14	3.306[08]	822.94	4.223[08]		
$6\,^1P_1$	222.96	1.752[08]	534.49	2.141[08]	1513.0	2.188[08]
			He-like neon			
$4\,^1P_1$	230.72	2.085[09]				
$5\,^1P_1$	158.03	9.007[08]	498.38	1.158[09]		
$6\,^1P_1$	134.91	4.761[08]	323.53	5.851[08]	916.91	5.995[08]
			He-like silicon			
$4\,^1P_1$	110.73	8.650[09]				
$5\,^1P_1$	75.772	3.734[09]	239.19	4.874[09]		
$6\,^1P_1$	64.673	1.967[09]	155.15	2.454[09]	440.25	2.530[09]
			He-like argon			
$4\,^1P_1$	64.821	2.448[10]				
$5\,^1P_1$	44.321	1.057[10]	140.01	1.375[10]		
$6\,^1P_1$	37.811	5.621[09]	90.688	6.985[09]	257.25	7.201[09]

Table 5

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$3\,^1D_2$		$4\,^1D_2$		$5\,^1D_2$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
			He-like carbon			
$4\,^1F_3$	749.60	6.005[09]				
$5\,^1F_3$	512.46	2.101[09]	1619.6	1.176[09]		
$6\,^1F_3$	437.25	1.026[09]	1049.2	6.061[08]	2978.7	3.391[08]
			He-like nitrogen			
$4\,^1F_3$	520.61	1.255[10]				
$5\,^1F_3$	355.90	4.329[09]	1124.8	2.407[09]		
$6\,^1F_3$	303.70	2.089[09]	728.86	1.226[09]	2070.3	6.846[08]
			He-like oxygen			
$4\,^1F_3$	382.50	2.377[10]				
$5\,^1F_3$	261.49	8.103[09]	826.41	4.477[09]		
$6\,^1F_3$	223.12	3.906[09]	535.46	2.278[09]	1520.8	1.269[09]
			He-like neon			
$4\,^1F_3$	231.38	6.952[10]				
$5\,^1F_3$	158.18	2.333[10]	499.88	1.276[10]		
$6\,^1F_3$	134.98	1.115[10]	323.92	6.436[09]	920.05	3.569[09]
			He-like silicon			
$4\,^1F_3$	110.88	3.441[11]				
$5\,^1F_3$	75.803	1.140[11]	239.51	6.276[10]		
$6\,^1F_3$	64.687	5.402[10]	155.22	3.138[10]	440.88	1.740[10]
			He-like argon			
$4\,^1F_3$	64.821	1.066[12]				
$5\,^1F_3$	44.319	3.517[11]	140.00	1.972[11]		
$6\,^1F_3$	37.817	1.671[11]	90.721	9.884[10]	257.52	5.514[10]

Table 6

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$4\,^1F_2$		$5\,^1F_3$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
	He-like carbon			
$5\,^1D_2$	1620.0	2.149[07]		
$6\,^1D_2$	1049.0	9.238[06]	2976.6	1.794[07]
	He-like nitrogen			
$5\,^1D_2$	1125.0	4.449[07]		
$6\,^1D_2$	728.87	1.893[07]	2070.1	3.623[07]
	He-like oxygen			
$5\,^1D_2$	826.54	8.348[07]		
$6\,^1D_2$	535.44	3.553[07]	1520.4	6.723[07]
	He-like neon			
$5\,^1D_2$	500.03	2.411[08]		
$6\,^1D_2$	323.95	1.022[08]	920.08	1.902[08]
	He-like silicon			
$5\,^1D_2$	239.70	1.207[09]		
$6\,^1D_2$	155.29	5.101[08]	441.19	9.351[08]
	He-like argon			
$5\,^1D_2$	140.19	3.850[09]		
$6\,^1D_2$	90.771	1.644[09]	257.71	3.000[09]

Table 7

Average wavelengths $\bar{\lambda}$ (Å) and radiative transition rates $\bar{A}$ (s^{-1}) for triplet-triplet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$2\,^3S$		$3\,^3S$		$4\,^3S$		$5\,^3S$	
Initial	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})
				He-like carbon				
$2\,^3P$	2272.3	5.695[07]						
$3\,^3P$	227.17	1.360[10]	8425.8	6.928[06]				
$4\,^3P$	173.26	6.187[09]	671.98	1.673[09]	20665.	1.586[06]		
$5\,^3P$	156.22	3.223[09]	472.13	9.483[08]	1474.3	3.821[08]	41075.	5.087[05]
$6\,^3P$	148.30	1.906[09]	406.54	5.738[08]	980.37	2.493[08]	2731.8	1.240[08]
				He-like nitrogen				
$2\,^3P$	1899.1	6.865[07]						
$3\,^3P$	161.21	2.851[10]	7004.7	8.445[06]				
$4\,^3P$	122.42	1.285[10]	474.41	3.565[09]	17138.	1.943[06]		
$5\,^3P$	110.22	6.676[09]	331.95	2.001[09]	1038.5	8.214[08]	33998.	6.261[05]
$6\,^3P$	104.57	3.907[09]	285.51	1.196[09]	688.27	5.255[08]	1925.3	2.652[08]
				He-like oxygen				
$2\,^3P$	1627.7	8.085[07]						
$3\,^3P$	120.32	5.315[10]	5979.5	1.003[07]				
$4\,^3P$	91.085	2.380[10]	352.73	6.726[09]	14605.	2.318[06]		
$5\,^3P$	81.916	1.234[10]	246.07	3.749[09]	770.85	1.559[09]	28950.	7.480[05]
$6\,^3P$	77.677	7.233[09]	211.42	2.239[09]	509.30	9.926[08]	1427.1	5.063[08]
				He-like neon				
$2\,^3P$	1256.6	1.077[08]						
$3\,^3P$	74.350	1.462[11]	4588.0	1.354[07]				
$4\,^3P$	56.042	6.493[10]	216.83	1.880[10]	11179.	3.147[06]		
$5\,^3P$	50.328	3.356[10]	150.65	1.038[10]	472.77	4.389[09]	22119.	1.020[06]
$6\,^3P$	47.692	1.957[10]	129.27	6.156[09]	311.20	2.759[09]	874.56	1.428[09]
				He-like silicon				
$2\,^3P$	833.99	1.790[08]						
$3\,^3P$	36.439	6.386[11]	3019.9	2.298[07]				
$4\,^3P$	27.340	2.812[11]	105.66	8.348[10]	7335.0	5.380[06]		
$5\,^3P$	24.515	1.449[11]	73.103	4.568[10]	229.82	1.964[10]	14486.	1.752[06]
$6\,^3P$	23.215	8.408[10]	62.637	2.690[10]	150.67	1.219[10]	424.68	6.401[09]
				He-like argon				
$2\,^3P$	590.47	2.990[08]						
$3\,^3P$	21.530	1.862[12]	2123.9	3.911[07]				
$4\,^3P$	16.118	8.165[11]	62.242	2.453[11]	5146.8	9.216[06]		
$5\,^3P$	14.442	4.201[11]	43.087	1.337[11]	135.22	5.794[10]	10158.	3.006[06]
$6\,^3P$	13.670	2.462[11]	36.792	7.943[10]	88.436	3.617[10]	249.32	1.912[10]

Table 8

Average wavelengths $\bar{\lambda}$ (Å) and radiative transition rates $\bar{A}$ (s^{-1}) for triplet-triplet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$2\,^3P$		$3\,^3P$		$4\,^3P$		$5\,^3P$	
Initial	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})
				He-like carbon				
$3\,^3S$	260.20	6.709[09]						
$4\,^3S$	189.29	2.607[09]	756.96	1.803[09]				
$5\,^3S$	168.44	1.279[09]	506.32	8.527[08]	1651.3	6.077[08]		
$6\,^3S$	159.01	7.324[08]	429.72	4.775[08]	1044.2	3.291[08]	3051.3	2.495[08]
				He-like nitrogen				
$3\,^3S$	180.71	1.292[10]						
$4\,^3S$	131.87	5.057[09]	524.44	3.510[09]				
$5\,^3S$	117.41	2.488[09]	352.07	1.671[09]	1142.6	1.191[09]		
$6\,^3S$	110.87	1.416[09]	299.15	9.307[08]	725.85	6.441[08]	2113.7	4.867[08]
				He-like oxygen				
$3\,^3S$	132.81	2.265[10]						
$4\,^3S$	97.125	8.917[09]	384.72	6.207[09]				
$5\,^3S$	86.515	4.395[09]	258.93	2.967[09]	837.34	2.114[09]		
$6\,^3S$	81.702	2.508[09]	220.12	1.659[09]	533.29	1.151[09]	1547.1	8.686[08]
				He-like neon				
$3\,^3S$	80.410	5.742[10]						
$4\,^3S$	58.967	2.275[10]	232.31	1.590[10]				
$5\,^3S$	52.552	1.124[10]	156.87	7.647[09]	504.93	5.450[09]		
$6\,^3S$	49.637	6.407[09]	133.47	4.272[09]	322.80	2.974[09]	932.62	2.242[09]
				He-like silicon				
$3\,^3S$	38.591	2.303[11]						
$4\,^3S$	28.376	9.200[10]	111.15	6.457[10]				
$5\,^3S$	25.302	4.558[10]	75.306	3.124[10]	241.20	2.226[10]		
$6\,^3S$	23.902	2.592[10]	64.127	1.742[10]	154.78	1.217[10]	445.25	9.168[09]
				He-like argon				
$3\,^3S$	22.583	6.463[11]						
$4\,^3S$	16.624	2.591[11]	64.930	1.822[11]				
$5\,^3S$	14.825	1.286[11]	44.057	8.840[10]	140.79	6.297[10]		
$6\,^3S$	14.005	7.402[10]	37.519	4.991[10]	90.438	3.491[10]	259.31	2.627[10]

Table 9

Average wavelengths $\bar{\lambda}$ (Å) and radiative transition rates $\bar{A}$ (s^{-1}) for triplet-triplet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$2\,^3P$		$3\,^3P$		$4\,^3P$		$5\,^3P$	
Initial	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})
				He-like carbon				
$3\,^3D$	248.72	4.240[10]						
$4\,^3D$	186.72	1.412[10]	717.49	4.312[09]				
$5\,^3D$	167.40	6.554[09]	497.10	2.162[09]	1557.2	8.794[08]		
$6\,^3D$	158.48	3.650[09]	425.91	1.231[09]	1022.0	5.370[08]	2869.1	2.640[08]
				He-like nitrogen				
$3\,^3D$	173.92	8.729[10]						
$4\,^3D$	130.35	2.892[10]	501.17	8.966[09]				
$5\,^3D$	116.80	1.340[10]	346.61	4.472[09]	1087.1	1.838[09]		
$6\,^3D$	110.56	7.387[09]	296.87	2.518[09]	712.56	1.106[09]	2004.8	5.476[08]
				He-like oxygen				
$3\,^3D$	128.46	1.606[11]						
$4\,^3D$	96.148	5.304[10]	369.83	1.663[10]				
$5\,^3D$	86.121	2.454[10]	255.43	8.265[09]	801.82	3.422[09]		
$6\,^3D$	81.500	1.355[10]	218.67	4.657[09]	524.82	2.056[09]	1478.0	1.025[09]
				He-like neon				
$3\,^3D$	78.294	4.328[11]						
$4\,^3D$	58.491	1.424[11]	225.09	4.538[10]				
$5\,^3D$	52.360	6.580[10]	155.17	2.244[10]	487.70	9.392[09]		
$6\,^3D$	49.538	3.622[10]	132.76	1.259[10]	318.65	5.599[09]	898.87	2.815[09]
				He-like silicon				
$3\,^3D$	37.835	1.823[12]						
$4\,^3D$	28.206	5.994[11]	108.57	1.947[11]				
$5\,^3D$	25.233	2.768[11]	74.698	9.584[10]	235.08	4.058[10]		
$6\,^3D$	23.866	1.521[11]	63.871	5.361[10]	153.30	2.404[10]	433.20	1.219[10]
				He-like argon				
$3\,^3D$	22.209	5.216[12]						
$4\,^3D$	16.539	1.708[12]	63.659	5.604[11]				
$5\,^3D$	14.791	7.877[11]	43.756	2.752[11]	137.77	1.172[11]		
$6\,^3D$	13.987	4.358[11]	37.397	1.549[11]	89.728	6.979[10]	253.57	3.556[10]

Table 10

Average wavelengths $\bar{\lambda}$ (Å) and radiative transition rates $\bar{A}$ (s^{-1}) for triplet-triplet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$3\,^3D$		$4\,^3D$		$5\,^3D$	
Initial	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})	$\bar{\lambda}$ (Å)	$\bar{A}$ (s^{-1})
			He-like carbon			
$4\,^3P$	762.96	2.928[08]				
$5\,^3P$	515.31	1.248[08]	1651.1	1.530[08]		
$6\,^3P$	438.15	6.627[07]	1055.6	7.679[07]	3035.4	7.732[07]
			He-like nitrogen			
$4\,^3P$	528.55	5.841[08]				
$5\,^3P$	357.58	2.495[08]	1143.6	3.069[08]		
$6\,^3P$	304.27	1.313[08]	732.93	1.531[08]	2106.8	1.543[08]
			He-like oxygen			
$4\,^3P$	387.61	1.049[09]				
$5\,^3P$	262.56	4.486[08]	838.50	5.537[08]		
$6\,^3P$	223.47	2.367[08]	537.98	2.770[08]	1543.6	2.795[08]
			He-like neon			
$4\,^3P$	233.88	2.734[09]				
$5\,^3P$	158.69	1.170[09]	505.81	1.454[09]		
$6\,^3P$	135.14	6.155[08]	325.18	7.260[08]	931.55	7.350[08]
			He-like silicon			
$4\,^3P$	111.78	1.112[10]				
$5\,^3P$	75.981	4.765[09]	241.66	5.979[09]		
$6\,^3P$	64.738	2.499[09]	155.67	2.981[09]	445.11	3.031[09]
			He-like argon			
$4\,^3P$	65.268	3.139[10]				
$5\,^3P$	44.400	1.346[10]	141.08	1.691[10]		
$6\,^3P$	37.829	7.135[09]	90.907	8.522[09]	259.41	8.671[09]

Table 11

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for triplet-singlet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$1\,^1S_0$		$2\,^1S_0$		$3\,^1S_0$		$4\,^1S_0$		$5\,^1S_0$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
					He-like carbon					
$2\,^3P_1$	40.751	2.696[07]								
$3\,^3P_1$	35.086	7.831[06]	252.41	4.524[05]						
$4\,^3P_1$	33.477	3.289[06]	187.57	1.985[05]	729.09	6.230[04]				
$5\,^3P_1$	32.786	1.699[06]	167.75	1.035[05]	499.63	3.397[04]	1584.5	1.517[04]		
$6\,^3P_1$	32.423	1.086[06]	158.68	6.608[04]	426.92	2.187[04]	1028.8	1.014[04]	2927.8	5.502[03]
					He-like nitrogen					
$2\,^3P_1$	29.095	1.346[08]								
$3\,^3P_1$	24.970	3.984[07]	176.50	2.357[06]						
$4\,^3P_1$	23.802	1.684[07]	131.04	1.041[06]	508.76	3.279[05]				
$5\,^3P_1$	23.301	8.669[06]	117.15	5.415[05]	348.40	1.783[05]	1104.6	7.979[04]		
$6\,^3P_1$	23.038	5.292[06]	110.80	3.312[05]	297.61	1.100[05]	716.78	5.108[04]	2039.8	2.775[04]
					He-like oxygen					
$2\,^3P_1$	21.810	5.352[08]								
$3\,^3P_1$	18.674	1.605[08]	130.28	9.667[06]						
$4\,^3P_1$	17.788	6.811[07]	96.676	4.290[06]	374.99	1.354[06]				
$5\,^3P_1$	17.407	3.506[07]	86.409	2.231[06]	256.69	7.360[05]	813.60	3.298[05]		
$6\,^3P_1$	17.208	2.093[07]	81.710	1.337[06]	219.24	4.451[05]	527.78	2.068[05]	1501.8	1.124[05]
					He-like neon					
$2\,^3P_1$	13.555	5.253[09]								
$3\,^3P_1$	11.570	1.604[09]	79.265	9.896[07]						
$4\,^3P_1$	11.010	6.840[08]	58.785	4.421[07]	227.74	1.399[07]				
$5\,^3P_1$	10.769	3.523[08]	52.528	2.303[07]	155.83	7.608[06]	493.68	3.414[06]		
$6\,^3P_1$	10.644	2.067[08]	49.664	1.357[07]	133.06	4.526[06]	320.14	2.105[06]	910.80	1.145[06]
					He-like silicon					
$2\,^3P_1$	6.6878	1.550[11]								
$3\,^3P_1$	5.6884	4.798[10]	38.172	3.047[09]						
$4\,^3P_1$	5.4073	2.054[10]	28.299	1.369[09]	109.49	4.337[08]				
$5\,^3P_1$	5.2867	1.059[10]	25.282	7.145[08]	74.902	2.364[08]	237.15	1.061[08]		
$6\,^3P_1$	5.2236	6.161[09]	23.900	4.179[08]	63.950	1.396[08]	153.77	6.498[07]	437.31	3.536[07]
					He-like argon					
$2\,^3P_1$	3.9685	1.782[12]								
$3\,^3P_1$	3.3691	5.486[11]	22.341	3.548[10]						
$4\,^3P_1$	3.2007	2.343[11]	16.563	1.593[10]	64.040	5.046[09]				
$5\,^3P_1$	3.1285	1.206[11]	14.796	8.305[09]	43.814	2.748[09]	138.68	1.234[09]		
$6\,^3P_1$	3.0907	7.001[10]	13.987	4.848[09]	37.408	1.620[09]	89.929	7.542[08]	255.70	1.620[09]

Table 12

Wavelengths λ (Å) and radiative transition rates A (s^{-1}) for singlet-triplet transitions in He-like ions. Numbers in brackets represent powers of 10.

Final	$2\,^3P_1$		$3\,^3P_1$		$4\,^3P_1$		$5\,^3P_1$	
Initial	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})	λ (Å)	A (s^{-1})
				He-like carbon				
$3\,^1S_0$	252.51	1.209[05]						
$4\,^1S_0$	187.60	4.961[04]	730.80	3.665[04]				
$5\,^1S_0$	167.76	2.484[04]	500.31	1.803[04]	1589.25	1.313[04]		
$6\,^1S_0$	158.68	1.418[04]	427.37	1.010[04]	1030.55	7.273[03]	2937.4	5.558[03]
				He-like nitrogen				
$3\,^1S_0$	176.14	6.094[05]						
$4\,^1S_0$	130.85	2.502[05]	508.97	1.898[05]				
$5\,^1S_0$	117.00	1.253[05]	348.48	9.349[04]	1105.9	6.858[04]		
$6\,^1S_0$	110.66	7.156[04]	297.66	5.239[04]	717.26	3.803[04]	2042.9	2.900[04]
				He-like oxygen				
$3\,^1S_0$	129.87	2.446[06]						
$4\,^1S_0$	96.463	1.005[06]	374.80	7.768[05]				
$5\,^1S_0$	86.240	5.033[05]	256.61	3.828[05]	813.84	2.823[05]		
$6\,^1S_0$	81.558	2.874[05]	219.17	2.145[05]	527.87	1.566[05]	1502.8	1.194[05]
				He-like neon				
$3\,^1S_0$	78.964	2.442[07]						
$4\,^1S_0$	58.632	1.003[07]	227.482	7.953[06]				
$5\,^1S_0$	52.407	5.025[06]	155.721	3.920[06]	493.51	2.911[06]		
$6\,^1S_0$	49.556	2.870[06]	132.991	2.198[06]	320.08	1.616[06]	910.78	1.234[06]
				He-like silicon				
$3\,^1S_0$	38.058	7.402[08]						
$4\,^1S_0$	28.241	3.037[08]	109.41	2.461[08]				
$5\,^1S_0$	25.236	1.521[08]	74.869	1.213[08]	237.13	9.057[07]		
$6\,^1S_0$	23.859	8.682[07]	63.926	6.800[07]	153.76	5.028[07]	437.40	3.845[07]
				He-like argon				
$3\,^1S_0$	22.304	8.679[09]						
$4\,^1S_0$	16.543	3.557[09]	64.050	2.881[09]				
$5\,^1S_0$	14.781	1.780[09]	43.818	1.420[09]	138.77	1.058[09]		
$6\,^1S_0$	13.973	1.016[09]	37.409	7.957[08]	89.963	5.875[08]	255.92	4.488[08]

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